Molecular Rods

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Synthesis and Conformational Study of Water-Soluble, Rigid, Rodlike Oligopiperidines**

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Herein, we describe the preparation of oligopiperidines as a new family of water-soluble, rigid oligomers. The design of molecules with nanometer dimensions, defined shapes, and physical properties (solubility, conductivity, etc.) is a matter of considerable interest in macromolecular chemistry.[1,2] "Molecular rods" are rigid, linear macromolecules that constitute promising materials for applications in nanotechnology, such as spacers, wires, and construction elements.[3] The poor water solubility of many current examples of molecular rods[1,4] limit their applications, particularly in biology. Only a few bio-oligomers exhibit a rigid-rod structure,[2c] of which oligoprolines, which have been considered the most rigid,[5] have been used as spacers in biochemistry.[6] The structure of these compounds is, however, still a subject of discussion. Levins and Schafmeister reported the synthesis of a water-soluble molecular rod based on fused diketopiperazine oligomers starting from a complex building block.[7]

We hypothesized that an oligomeric backbone of piperidine rings would be a rigid rod, with the piperidine moieties adopting chair conformations in aqueous solution.[8] We have developed a synthesis of representative members of this class of molecules and investigated their conformations in polar solvents, including deuterated water. We are particularly interested in the possibility that they might serve as extended,

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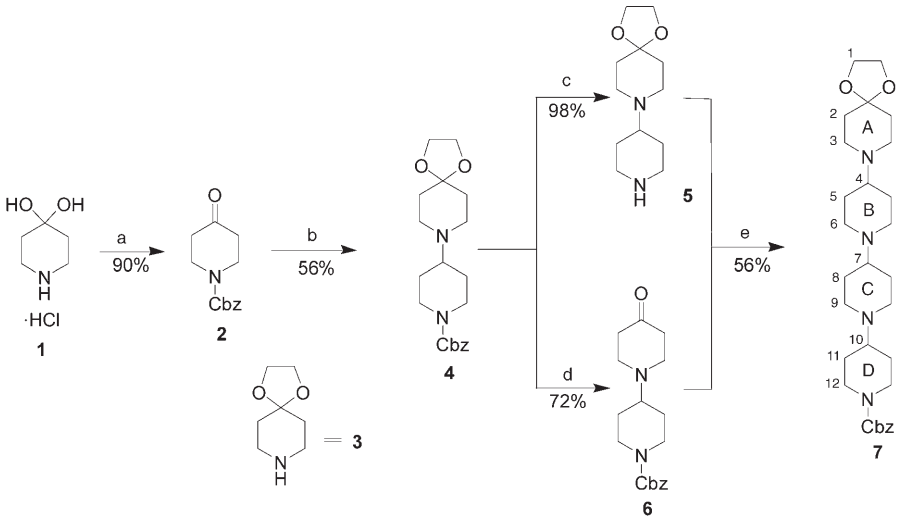
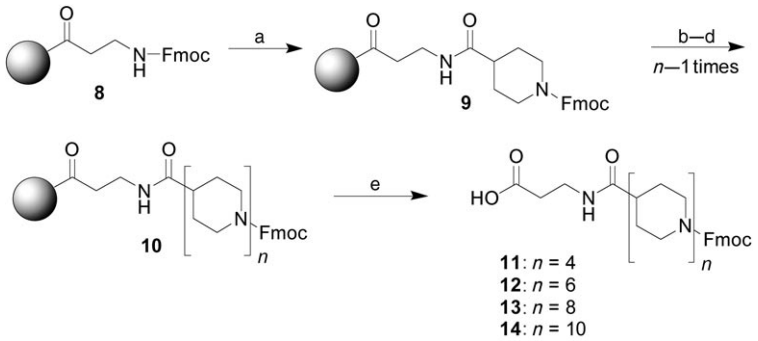
water-soluble linkers or scaffolds for the oligovalent display of ligands.

Scheme 1 outlines the strategy used to synthesize the oligopiperidines in solution. In this strategy, elongation is based on iterative reductive amination. We protected the commercially available 4,4-piperidinediol hydrochloride (**1**) with a benzyloxycarbonyl (Cbz) group to obtain **2**. This compound was allowed to react with 1,4-dioxa-8-aza-spiro-[4.5]decane (**3**) in the presence of triacetoxyborohydride to afford piperidinopiperidin-4-one **4** diprotected with a cyclic ketal and a Cbz group.[9] Compound **4** led to two further intermediates. Its catalytic hydrogenation yielded compound **5**, and treatment of which with a concentrated aqueous HCl solution afforded compound **6**. Reductive amination of **5** and **6** yielded the tetramer derivative **7**.



Scheme 1. Solution-phase synthesis of tetrapiperidine **7**. a) Na_2CO_3, CbzCl; b) 1,4-dioxa-8-aza-spiro-[4.5]decane (**3**), $NaBH(OAc)_3$, 1,2-dichloroethane; c) Pd/C, H_2, EtOH; d) concentrated HCl, 0 °C to room temperature, 20 min; e) $NaBH(OAc)_3$, 1,2-dichloroethane.

We used solid-phase techniques to synthesize oligopiperidines up to ten units in length (Scheme 2). Solid-phase synthesis of oligopiperidine was performed on preloaded Fmoc-β-Ala Wang resin **8** (Fmoc = 9-fluorenylmethoxycarbonyl) on a 50-μmol scale. After deprotection with 20% piperidine in dimethylformamide (DMF), the resin was allowed to react with the *N*-Fmoc-protected isonipecotic acid in the presence of benzotriazolyl-*N*-oxy-tris(dimethylamino)phosphonium (BOP reagent) and the Hunig base to afford **9**. We assembled building blocks to form the molecular rod by using a sequential procedure: deprotection, reductive amination with Fmoc-4-piperidone, and capping with acetic anhydride. The resin was then washed and dried prior to treatment with trifluoroacetic acid (TFA)/H_2O (95:5) for 2 h. HPLC purification on a C_{18} column and lyophilization afforded pure oligopiperidines **10** and **11**.



Scheme 2. General procedure for the solid-phase synthesis of oligopiperidine. a) Fmoc-isonipecotic acid, BOP, $NEt(iPr)_2$ in DMF; b) 20% piperidine in DMF, 20 min; c) Fmoc-4-piperidone, $NaBH(OAc)_3$ in 1,2-dichloroethane, 2×60 min; d) acetic anhydride, $NEt(iPr)_2$, CH_2Cl_2; e) TFA/H_2O (95:5).

The structure of **7** was investigated by 1D and 2D NMR spectroscopy in CD_3OD. This solvent was used because it produced a larger dispersion of chemical shifts than solvents such as $CDCl_3$ or D_2O. The spin systems of all four piperidine residues were unambiguously identified from COSY experiments. The sequence was assigned on the basis of NOESY experiments (mixing time = 400 ms) and was deduced from the strong NOE interaction connectivities between piperidine rings. Analysis of 1D spectra recorded between 273 and 323 K at 10 K increments revealed that the coupling values are only weakly affected by temperature changes; we infer that a single conformation dominates over this range of temperature. In the ^1H NMR spectrum recorded at room temperature, in CD_3OD, and at 500 MHz (Figure 1), the axial and equatorial protons of the piperidine rings B, C, and D (H5, H6, H8, H9, H11, and H12) are discernible. The eight ring protons (H2 and H3) of the piperidine ring A appear as two triplets at $\delta = 2.66$ and 1.71 ppm; this observation indicates that the axial and equatorial positions in this ring exchange rapidly on the NMR time scale through combined nitrogen inversion and chair–chair inversion. Rings B–D all display approximately the same series of signals with 1) a triplet of triplets for H4, H7, and H10, all in axial positions and 2) significant chemical-shift differences ($0.4 < \Delta\delta_{ae} < 1.4$ ppm) between the axial and the equatorial sites of each methylene group with the axial proton at higher field. These characteristics provide strong evidence that all of these rings have the same chair conformation.[10] The chemical-shift difference between H12a and H12e in ring D is accentuated by the location of H12e in the shielding zone of the Cbz group.

NOESY experiments at 298 K with a mixing time of 400 ms yielded additional information about the three-dimensional structure of the tetrapiperidine **7**. Several inter- and intraresidue

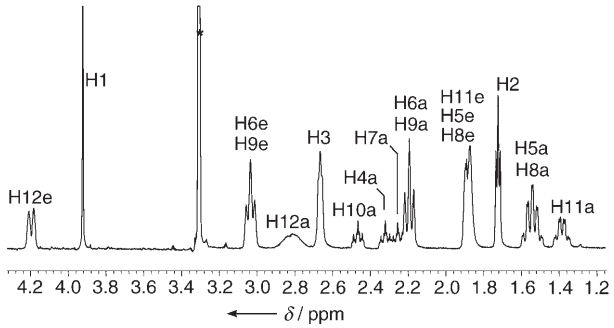


Figure 1. ^{1}H NMR spectrum (500 MHz) of tetrapiperidine derivative **7** in CD_3OD.

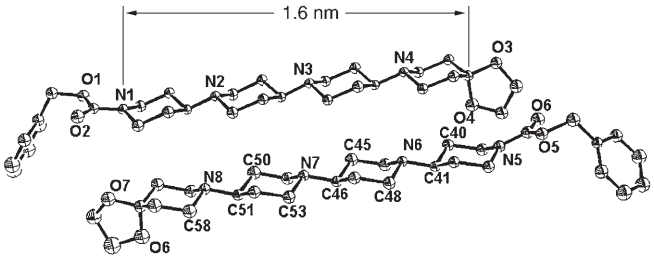


Figure 3. ORTEP diagram of the crystal structure of **7** (50% thermal ellipsoids; protons are omitted for clarity). Selected distances [Å] and torsion angles [°]: N5-N6 4.273, N6-N7 4.339, N7-N8 4.357; C48-N6-C41-C40 178.6(5), C53-N7-C46-C45 179.9(5), C58-N8-C51-C50 179.9(5).

NOE interactions were extracted and are consistent with the presence of a rodlike conformation (Figure 2). Intraresidue NOE interactions confirmed the existence of a chair geometry in piperidine rings. Interresidue NOE interactions

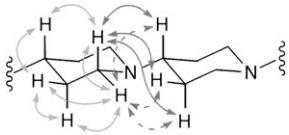


Figure 2. Intra- and interresidue NOE interactions found between two piperidine units.

revealed: 1) a linear structure with each piperidine unit in an equatorial position and 2) the existence of several conformations of the N–C bond between each piperidine unit that are probably the three minimum-energy staggered conformations of this bond.[11] The same characteristic NOE interactions were found with a small model molecule, methylpiperidinopiperidine (see the Supporting Information). The ^{1}H NMR spectra of **7** and methylpiperidinopiperidine (see the Supporting Information) in deuterated water exhibit approximately the same characteristic pattern of signals as that in CD_3OD, with significant chemical-shift differences between axial and equatorial protons from the same methylene group; these characteristics indicate the presence of a unique structure in methanol and water. IR analysis of the oligopiperidine **7** in $CDCl_3$ and the Bohlmann band at 2814 cm^{-1} (see the Supporting Information) provide further evidence in favor of an extended structure in which the piperidine rings are in equatorial positions.[10a] Collectively, these data strongly suggest that **7** adopts a well-defined rodlike structure in solution.

The slow evaporation of a solution of **7** in deuterated methanol yielded crystals of the unprotected base suitable for X-ray structural determination.[12] The unit cell contains two tetrapiperidine **7** molecules. The conformations of these two molecules differ in the arrangement of their Cbz groups. Their ORTEP representations clearly reveal linear rodlike structures (Figure 3). The molecules each consist of four piperidine rings in chair conformations. All piperidine segments occupy the equatorial position on each connected ring and are separated by approximately 4.3 Å.

Molecular dynamics (MD) simulations on the oligomer **7** were performed at 300, 350, and 400 K to characterize the conformational ensemble of the oligopiperidine as a function of increasing temperature. For each temperature, the system was equilibrated for 10 ps using a 2-fs time step, during which time the temperature was ramped from 0 K to the final system temperature (300, 350, or 400 K). Production simulations were run for 1 ns using a 2-fs time step. Snapshots of the system were written out every ten steps to insure that fine details of the system were observed. To determine how linear the geometry of the molecule remained during each simulation, two metrics were used. The first is the length of the major axis, defined as the distance between two carbon atoms at the opposite ends of the molecule (Table 1), which was

Table 1: Statistics of the major-axis length (measured from the carbon atoms labeled A and B) distributions of **7** observed in three MD simulations.

Temperature [K]	Mean length [Å]	Standard deviation
300	15.0	0.4
350	14.9	0.7
400	14.9	0.9

measured for each snapshot in each MD trajectory. The second is the major axis angle, formed by the previously defined major-axis carbon atoms and a central nitrogen atom in the molecule (see the Supporting Information). These two values characterize the overall geometry of the molecule during the simulations, thus describing its tolerance for stretching, compressing, and bending. The distributions of the oligopiperidine lengths remain fairly invariant across all three temperatures simulated (Table 1), thus indicating that the linear geometry of this molecule, and its corresponding ability to resist stretching and compressing, is stable across a large range of temperatures.

Furthermore, the values of the major-axis angles indicate that the molecule remains very extended through simulations

at all three temperatures. At higher temperature simulations, the distribution of the major axis angle values has an increased mean and a decreased variance. This implies that as the temperature increases, the oligopiperidine structure tends to bend less and remain slightly more fully extended. Altogether, these data demonstrate that these oligopiperidine molecules adopt a stable linear conformation. Visual inspection of the simulation trajectories confirms that the molecule retains an extended structure throughout the entire simulation. Although rotations about the C–N bonds occur, these rotations result in only small deviations around the linear geometry of the molecule.

This report describes a simple, inexpensive, and widely accessible method for the preparation of rigid, rodlike oligopiperidines with a defined length of up to ten units (4.3 nm length). This oligomeric system does not require control of the stereochemistry at the Cγ position of the piperidine ring, but rather allows the molecule to equilibrate into the proper conformations. Because of their structure, we expect these molecules to be more resistant to proteolysis than polyprolines. These well-defined, water-soluble molecules may provide access to materials with well-defined structures (e.g., rigid linkers, construction elements, etc.).

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[1] a) P. F. H. Schwab, M. D. Levin, J. Michl, *Chem. Rev.* **1999**, *99*, 1863 – 1933; b) J. S. Moore, *Acc. Chem. Res.* **1997**, *30*, 402 – 413; c) J. M. Tour, *Acc. Chem. Res.* **2000**, *33*, 791 – 804.
[2] a) S. H. Gellman, *Acc. Chem. Res.* **1998**, *31*, 173 – 180; b) R. P. Cheng, S. H. Gellmann, W. F. DeGrado, *Chem. Rev.* **2001**, *101*, 3219 – 3232; c) D. J. Hill, J. M. Matthiew, R. B. Prince, T. S. Hughes, J. S. Moore, *Chem. Rev.* **2001**, *101*, 3893 – 4011.
[3] N. Sakai, J. Mareda, S. Matile, *Acc. Chem. Res.* **2005**, *38*, 79 – 87.
[4] a) N. Aratani, H. S. Cho, T. K. Ahn, S. Cho, D. Kim, H. Sumi, A. Osuka *J. Am. Chem. Soc.*, **2003**, *125*, 9668 – 9681; b) C. Xu, A. Wakamiya, S. Yamaguchi, *J. Am. Chem. Soc.* **2005**, *127*, 1638 – 1639.
[5] a) L. Stryer, R. P. Haugland, *Proc. Natl. Acad. Sci. USA* **1967**, *58*, 719 – 726; b) B. Schuler, E. A. Lipman, P. J. Steinbach, M. Kumke, W. A. Eaton, *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 2754 – 2759.
[6] a) P. S. Arora, A. Z. Ansari, T. P. Best, M. Ptashne, P. Dervan, *J. Am. Chem. Soc.* **2002**, *124*, 13067 – 13071; b) H. Ungar-Waron, D. Gurari, E. Hurwitz, M. Sela, *Eur. J. Immunol.* **1973**, *4*, 201 – 205.
[7] C. G. Levins, C. E. Schafmeister, *J. Am. Chem. Soc.* **2003**, *125*, 4702 – 4703.
[8] R. J. Willemse, J. J. Piet, J. M. Warman, F. Hartl, J. W. Verhoeven, A. M. Brouwer, *J. Am. Chem. Soc.* **2000**, *122*, 3721 – 3730.
[9] A. F. Abdel-Magid, K. G. Carson, B. D. Harris, C. A. Maryanoff, R. D. Shah, *J. Org. Chem.* **1996**, *61*, 3849 – 3862.
[10] a) F. W. Vierhapper, E. L. Eliel, *J. Org. Chem.* **1979**, *44*, 1081 – 1087; b) E. L. Eliel, F. W. Vierhapper, *J. Am. Chem. Soc.* **1975**, *97*, 2424 – 2430; c) E. L. Eliel, F. W. Vierhapper, *J. Am. Chem. Soc.* **1974**, *96*, 2257 – 2259.
[11] C. Jaime; E. J. Ōsawa, *J. Chem. Soc. Chem. Commun.* **1983**, *12*, 708 – 709.
[12] Crystal data: $C_{30}H_{46}N_4O_4$, $M_r = 526.71\ g\,mol^{-1}$, colorless needle, crystal size: $0.10 \times 0.08 \times 0.04\ mm^3$, $a = 9.1261(14)$, $b = 11.4111(17)$, $c = 105.305(16)$ Å, $\alpha = 90$, $\beta = 90$, $\gamma = 90°$, $V = 10966(3)$ Å^3, $T = 193(2)$ K, orthorhombic, space group *Pbca*, $Z = 16$, $\rho_{calcd} = 1.276\ Mg\,m^{-3}$. Crystallographic data were collected using a Bruker SMART CCD (charge-coupled device) based diffractometer equipped with an Oxford Cryostream low-temperature apparatus operating at 193 K, $\lambda = 0.71073$ Å. 32596 measured reflections, 5102 unique ($R_{int} = 0.0505$), the structure was solved by direct methods and refined by full matrix least squares on F^2 for all data to $R_1 = 0.0850$ ($I > 2\sigma(I)$) and $wR_2 = 0.1729$ ($I > 2\sigma(I)$). CCDC 263974 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

